NGC 2915. II. A Dark Spiral Galaxy With A Blue Compact Dwarf Core

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ABSTRACT

This paper presents *Australia Telescope Compact Array* H I synthesis observations of the weak blue compact dwarf (BCD) galaxy NGC 2915. It is shown that NGC 2915 has the H I properties of a late type spiral galaxy (Sd - Sm), including a double horn global profile, and H I spiral arms. The H I extends out to over five times the Holmberg radius, and 22 times the exponential scale length in the B band. The optical counterpart corresponds to a central H I bar. The H I distribution and kinematics are discussed in detail. A rotation curve is derived and fitted with a mass model consisting of a stellar disk, a neutral gas disk, and a dark matter (DM) halo. The DM halo dominates at nearly all radii. The total mass to blue light ratio, $\mathcal{M}_T/L_B = 76$ within the last measured point. Thus NGC 2915 is one of the darkest disk galaxies known. The complex H I dynamics of the central region results in a high uncertainty of many of the fitted

parameters. Nevertheless it is clear that the core of the DM halo is unusually dense ($\rho_0 \approx 0.1\,\mathcal{M}_\odot\,\mathrm{pc}^{-3}$) and compact ($R_c \approx 1$ kpc). The neutral gas component, with mass $M_g = 1.27 \times 10^9\,\mathcal{M}_\odot$ is probably more massive than the stellar disk. Split and broad H I lines (velocity dispersion $\approx 35\,\mathrm{km\,s^{-1}}$) are seen in the central region. Pressure support is probably significant, and it is not clear whether the core is in equilibrium. Beyond the optical disk the average H I line of sight velocity dispersion is 8 $\mathrm{km\,s^{-1}}$, which is normal for disk galaxies. NGC 2915 does not obey the Tully-Fisher (1977) relation, being underluminous for its $V_{\mathrm{rot}} = 88\,\mathrm{km\,s^{-1}}$ by a factor of nine. It also does not obey the star formation threshold model of Kennicutt (1989), when only the neutral gas is considered. A simple H I surface density threshold of $\Sigma_{\mathrm{HI,crit}} \approx 10^{21}\,\mathrm{cm}^{-2}$ adequately describes the location of current star formation. Although the H I properties of NGC2915 are extreme relative to normal galaxies they appear less extreme in comparison to other BCDS, which have similar radial profiles of H I density and velocity dispersion, and H I extending well beyond the optical disk.

1. Introduction

The quest for understanding dark matter (DM) halos of galaxies using H I as a probe is predominantly weighted towards spiral and dwarf irregular galaxies. The H I rich blue compact dwarf (BCD; Thuan and Martin, 1981) class has been largely ignored, and is under represented in H I synthesis studies. This may be because their small optical angular sizes, often smaller than typical synthesized beam sizes, suggests that they will not be well resolved at λ21 cm. Also, only 8% of the BCDs in Thuan and Martin's sample have double horn profiles indicative of extended rotating disks, suggesting that they are not ideal candidates for DM studies. Some important H I synthesis observations of BCDs, and similar galaxies, have been made (e.g. Taylor *et al.*, 1993; 1995; 1996; Hunter *et al.*, 1994) but their primary aims were other than to search for DM.

Here we present H I observations of NGC 2915 whose optical properties were presented by Meurer *et al.* (1994; paper I). There it was shown to be a weak BCD, that is its integrated star formation rate is only 0.05 $\mathcal{M}_{\odot}$ yr^{-1}. Most of this star formation is near the very center of the galaxy with some enhanced star formation along the major axis to the SE of the center. NGC 2915 resolves into stars; the brightest of these yields the distance $D = 5.3 \pm 1.3$ Mpc. At this distance $1''$ corresponds to 26 pc, and $1'$ corresponds to 1.54 kpc. Previous single dish H I observations indicate that it has a very extended H I disk (Becker *et al.* 1988). The H I observations presented here were made primarily to determine NGC 2915's H I rotation curve, and from it, constrain the structure of its DM halo. In addition we wish to examine how the H I properties of this BCD differ from other types of galaxies, and whether they give any indication of what regulates star formation in BCDs.

The observations are presented in §2.. Section §3. presents an overview of the H I properties. The dynamics of the ISM are analyzed in §4.. The rotation curve is measured, pressure support corrections applied and mass models fitted. Section §5. presents a discussion of the results including a comparison with other galaxies, a discussion of the Tully-Fisher (1977) relation and the star-formation threshold law. Our conclusions are summarized in §6.. In the Appendix we discuss a possible interaction partner of NGC 2915.

2. Observations and Data Reduction

NGC 2915 was observed with three configurations of the Australia Telescope Compact Array using all six antennas. However, baselines with antenna 6, (which gives the longest baselines - up to 6 km) were discarded since they produced insignificant correlation amplitudes. The dual polarization AT receiver was employed with the correlator set to 256 channels per polarization, and with each channel separated by 15.7 KHz (3.31 km/s). The observing logs for the three configurations are given in Table 1. The integration time was 20 s per visibility measurement. Some data in each run were lost to equipment failure and weather.

The data were reduced using standard software in the *AIPS* package (ATNF version). The relevant tasks used are noted here in parenthesis. Bad or suspect data were edited out (TVFLAG, SPFLAG). Temporal gain and phase drifts were calibrated (CALIB) using the secondary calibrator, 0906-682 which was observed at 50 min. intervals for 3–6 min. Spectral variations in the calibration were determined from the observations of 1934-638 and 0407-658 (BPASS). The absolute flux level was set by the primary calibrator 1934-638 (SETJY, GETJY; flux reference: Walsh, 1992). The calibration was checked for the 1.5 km array data set using 0407-658 which is also a flux standard (Walsh, 1992). The calibration agreed to within 2% with the adopted 1934-638 calibration. The calibrations were applied

and the two polarization channels combined to form Stokes "I" data sets (SPLIT). The continuum was fitted and subtracted in the UV plane (UVLSF) and the resultant continuum and line data sets were averaged in time (UVAVG) to one minute per visibility. The line data sets were shifted to the heliocentric rest frame (CVEL), and the data from the three runs were combined (DBCON). The data were imaged and "cleaned" (MX; Schwab, 1984; see also Clark, 1980; Högbom, 1974) to about the noise level per resultant channel to make both uniform and natural weighted data cubes (hereafter UN and NA respectively). For the NA cube, two spectral channels at a time were averaged at the imaging stage. The UN data was imaged at full spectral resolution. The beam sizes at the 50% level are $W_{50} = 45''$ (circular) for the NA data cube and $W_{50} = 27'' \times 23''$ (PA = 0°) for the UN cube. The final cubes were made by reconvolving the clean component images with two-dimensional Gaussian beams having the above sizes. Planes of the resultant NA data cube are shown in Fig. 1.

From each cube, maps of total intensity, mean velocity, and line broadening were constructed from the zeroth, first, and second moments of the data cubes (w.r.t. velocity; MOMNT). The moment maps and data cubes were then corrected for the fall-off in primary beam response with distance from the pointing center (PBCOR). Table 2 summarizes some of the properties of the NA and UN data sets including the beam size, pixel size and noise level in the resultant data cubes.

In order to check the moment analysis results, single Gaussian fits to the UN data cube were made (XGAUS). As a further check, and to examine the line profiles in detail the UN data cube was block averaged into $30'' \times 30''$ pixels, and all the resulting profiles were examined and fit with a multiple Gaussian fitting algorithm using the *IRAF* program SPLOT.

3. Overview of HI properties

A cursory examination of the H I properties of NGC 2915 shows that they are very different from its optical properties. Figure 2 (plate XXXX) shows three H I surface density maps, plotted as grey scales. Panel a shows the NA moment 0 map (45″ beam); panel b, the UN moment 0 map ($27'' \times 23''$ beam), and panel c, the XGAUS peak amplitude map. NGC 2915 clearly has a spiral morphology, and this is most readily apparent in the NA map. There appears to be two arms which can be traced back to the ends of central bar structure. Figure 3 shows a contour plot of the NA moment 0 map, while the UN moment 0 contours are shown in Fig. 4 (Plate XXXX) overlaid on an I band image obtained with the Anglo-Australian Telescope. This clearly shows that the H I, including the spiral arms, extends well beyond the optical extent of NGC 2915.

The prominent central bar is about 2.5′ (3.9 kpc) long. It is most clearly seen in panel a of Fig. 2. The velocity field, analyzed in §4.1., shows the signature of an oval distortion demonstrating that this is a real bar, and not a highly inclined disk. The bar is resolved into two clouds in the UN data as can be seen in the bottom two panels of Fig. 2 and Fig. 4. Each of these clouds has a neutral gas mass[1] of $\sim 2.5 \times 10^7$ $\mathcal{M}_\odot$ (1.4×10^7 $\mathcal{M}_\odot$ if a local background is subtracted) which is the majority of the mass in the bar. They are located 17″ NW and 36″ SE of cluster 1 (paper I). They encompass many of the embedded objects discussed in paper I and bracket the brighter central clusters as well as some of the peculiar structure on the SE side of the galaxy. The faint "jets", first mentioned by Sérsic *et al.* (1977) (cf. Fig. 2 paper I) project outwards from the core of these clouds. The XGAUS map in panel c of Fig. 2 is very noisy, and clearly shows only the highest S/N features. In this map the morphology is reminiscent of a

[1]The neutral gas mass is the H I mass multiplied by 1.33 to correct for the neutral He content.

spiral with a bar interior to a detached ring.

The optically visible portion of NGC 2915 coincides in position, orientation, and size to the central bar. Thus while the exponential optical surface brightness profile (for $R > 35''$) implies a disk structure, the H I data suggests that the stars are in a bar configuration. This interpretation is consistent with the optical morphology (paper I) which shows enhanced star formation primarily in the center of the galaxy, but also along the optical major axis, or the bar ridge line. Such a distribution of star formation is common in barred galaxies (Friedli & Benz, 1995, and references therein).

There is a large "hole" $\sim 130'' \times 180''$ (3.4×4.6 kpc) located $310''$ (8.9 kpc) to the east of the galaxy's center. Examination of a position-velocity cut through this structure does not reveal split line profiles, indicating that it is probably not a kinematic shell, but an interarm clearing. The H I in NGC 2915 does not appear to be very porous, as is found to be the case in many nearby disk galaxies, such as HoII (Puche *et al.*, 1992). This may be largely a result of resolution; the HoII data have a resolution of 66 pc, and typical bubble sizes are a few hundred pc, while the linear resolution of our data is ten times worse (640 pc).

The velocity field from the NA and UN moment 1 maps are shown in Figs. 5 and 6 (Plate XXXX) respectively. They clearly show the expected pattern of a rotating disk. The disk must be warped as indicated by the twisting of the kinematic major and minor axes. Thus although there are closed velocity contours, it is not readily apparent whether these are due to a declining rotation curve, or the warped disk. The rotation curve is derived in detail in §4.1.. The NA and UN global velocity profiles are shown in Fig. 7. These were made from the data cubes by summing the flux in each channel within a "blanking aperture". The aperture was defined by eye using the total intensity map as a guide. The twin horned nature of the profile is the classic profile of a rotating disk. The bump near V_{sys} is due to the large central concentration of H I.

Figure 8 shows the line of sight velocity dispersion, b, map from the XGAUS profile fitting. It shows that b increases by several tens of $\mathrm{km\,s^{-1}}$ towards the center of NGC 2915. This is a much larger gradient than typically observed in spiral and irregular galaxies (Kamphuis, 1992; Lo *et al.*, 1993). These maps indicate that pressure support may be important to the dynamics of NGC 2915. The line profiles are discussed in detail in §4.2., while the pressure support, or asymmetric drift, corrections to the rotation curve are discussed in §4.3..

Table 2 presents some properties measured from our data. From the global H I profiles we measured the total line flux $\int SdV$, the corresponding H I mass, $\mathcal{M}_{\rm HI}$, the velocity widths at 50% and 20% of the maximum intensity, W_{50} and W_{20} respectively, and the systemic velocity V_{sys}. That $\int SdV$ from the UN and NA global profiles agree so well, indicates that the UN data is not missing much short spacing flux compared to the NA data. The H I mass, $\mathcal{M}_{\rm HI} = 9.6 \pm 0.2 \times 10^8\ \mathcal{M}_\odot$ from the NA data, is significantly higher than that derived by Becker *et al.* (1988), $\mathcal{M}_{\rm HI} = 7.0 \times 10^8$ (after adjusting to our adopted distance) using a low resolution H I map derived from Parkes 64m observations. We suspect that the flux difference is due to the lower signal to noise ratio of their observations and perhaps inadequacies in their beam profile correction. The systemic velocities measured from the global profile, V_{sys}(global), and the tilted ring analysis, V_{sys}(dynamical) (see §4.1.), agree well with each other, and also with the optical velocity $V_{sys}(\text{optical}) = 468 \pm 5\,\mathrm{km\,s^{-1}}$ reported in paper I.

From the total intensity maps we measure $R_{\rm HI}$, the radius where the face-on H I column density $N(HI) = 5 \times 10^{19}\,\mathrm{cm^{-2}}$, and $N_{\rm HI}(\max)$, the maximum H I face-on column density. The

correction to face-on is for the mean inclination $i = 59°$, as derived below. The remaining properties in Table 2 compare the H I and optical properties (paper I). $\mathcal{M}_{\rm HI}$ is compared to the B band luminosity, L_B, and $R_{\rm HI}$ is compared to the Holmberg radius $R_{\rm Ho}$ and B band exponential scale length α_B^{-1}. The resultant ratios quantify what is already clear: NGC 2915 is gas-rich and very extended in H I.

4. ISM Dynamics

4.1. Tilted ring analysis

The H I rotation curve was derived using the now standard tilted ring algorithm, ROTCUR (Begeman 1989), in a manner similar to that outlined by Martimbeau *et al.* (1994). The UN and NA first moment maps, and the UN-XGAUS velocity field were analyzed separately, using ring widths of 25″, and 45″ for the UN and NA data respectively. There are up to six parameters for each ring; the central coordinates X_c, Y_c, the systemic velocity V_{sys}, the inclination i, the position angle ϕ of the kinematic major axis (receding side), and the rotation velocity, $V_{\rm rot}$. The parameters were derived using five iterations of the algorithm. In the first iteration all parameters are allowed to be free. This iteration gives a feel for how the parameters vary with radius R. In the second iteration, i and ϕ are held fixed while the other parameters are allowed to vary. The aim of this iteration is to find the best average value of X_c, Y_c, and V_{sys}, which are then held fixed at a constant value for all subsequent iterations. The resultant mean V_{sys} values are reported in Table 2 as V_{sys}(dynamical). In the third iteration, new radial profiles of i, ϕ, and $V_{\rm rot}$ are derived. Smooth curves are drawn through these profiles and the interpolated values of these parameters are used as the initial guess for these parameters in the fourth iteration, which is meant to test how stable the solutions are to small changes in the initial guesses.

It was found that the NA-MOMNT and UN-XGAUS solutions are stable to small perturbations. However the inner three rings of the UN-MOMNT field ($R < 90''$) are not. No unique solutions could be found. This is due to the kinks in the central isovelocity contours seen in Fig. 6. Therefore we adopt the UN-XGAUS results for $R \leq 90''$, the UN-MOMNT results for $90'' < R \leq 390''$ and the NA results for $R > 390''$. Finally each half (approaching and receding) of the galaxy was analyzed separately. This final step allows the uncertainty of the parameters to be estimated from the level of asymmetry in the velocity field; the errors in the parameters are taken to be the absolute difference between the value for the full ring and either the receding or approaching half, whichever is larger. The $V_{\rm rot}$ errors estimated by this method are always larger than or equal to the formal errors from the least squares fitting. The formal errors in i and ϕ are occasionally larger than the asymmetry of field errors. In these cases the former is adopted.

The results in terms of i, ϕ and $V_{\rm rot}$ for each data set are shown in Fig. 9. The adopted fit parameters are tabulated in Table 3. The H I disk shows a strong warp in both ϕ ($\Delta\phi = 40°$) and i ($\Delta i = 25°$). The warp is strongest, especially in i, for $R \leq 150''$, with relatively mild warping ($\Delta\phi = 15°$, $\Delta i = 4°$) beyond this radius. The adopted rotation curve shows a rapid rise to $V_{\rm rot} \approx 80$ km s^{-1} at $R = 202.5''$. It then remains approximately constant until rising again for $R > 290''$. Figure 10 shows a position velocity cut through the NA data cube along the major axis ($\phi = -70°$). The second rise can be seen directly on both sides of the galaxy, demonstrating that it is real.

Figure 11 shows the residual maps from the ring fits. Local deviations from the fit have $|\Delta V_r| \lesssim 15$ km s^{-1}. The residuals in the inner portion show rings of mostly negative and mostly positive residuals at $R \approx 65''$ and $150''$ respectively. This indicates that V_{sys} varies with R, suggesting that the inner portions of the gal-

axy are not in equilibrium. Kamphuis (1992) finds V_{sys} variations in normal spiral galaxies, but at large radii. In the center where $V_{\rm rot}$ is low these deviations are large enough to cause the isovelocity contour twists and the problems in the UN-MOMNT fit noted above. The residuals along the minor axis have opposing signs up to $\approx \pm 10 \mathrm{km\,s^{-1}}$ on either side of the center (+ to the NE, − to the SW). This is a signature of an oval distortion[2]: the kinematic major and minor axes are non-orthogonal (Bosma, 1981). The effect can also be discerned in Figs 5,6. The distortion probably arises from the central bar, and is strongest for the rings with $200'' \lesssim R \lesssim 450''$. It shows that the orbits are not strictly circular for these rings, although one should bear in mind that the residuals are small compared to the amplitude of $V_{\rm rot} \approx 80\ \mathrm{km\,s^{-1}}$ at these radii.

4.2. Line profiles

The results of the automatic Gaussian fitting are shown in Fig. 8 which gives a map of b values from XGAUS. The b map is not symmetric about the center of NGC 2915. There is stronger line broadening on the SE side than the NW. The broadening is centered on the SE H I cloud (see Fig. 4).

XGAUS was set to make only single Gaussian fits. The SPLOT measurements were designed to test the XGAUS results and measure complex line profiles. The position of the splot fits are shown in Fig. 12, with the positions of profiles best fit by multiple Gaussians highlighted. The H I profiles are predominantly single peaked. The main region of split lines is confined to within $2'$ of the center, which is also where the lines become the broadest. Profiles at the position of both H I clouds are split. Thus the total H I width distribution (including splitting) is a bit more symmetric than the b map shown in Fig. 8. The average line split is $\overline{\Delta V_r} = 41\ \mathrm{km\,s^{-1}}$. A few representative profiles and their SPLOT fits are shown in Fig. 13.

Could the broad profiles be due to beam smearing of the observed steep rotation curve? This is not likely, because the knee in the rotation curve is four to six beam widths from the center, and thus the central velocity gradient is not that steep. Beam smearing only shows its effects over one to two beam widths. We verified this by simulations of the data including the effects of beam smearing on the UN data cube. A change in $V_{\rm rot}$ of 80 $\mathrm{km\,s^{-1}}$ in one beam width can result in $b = 27\ \mathrm{km\,s^{-1}}$. But we can rule out such a steep rotation curve, because it would require the knee in the rotation curve to be at $R = 50''$. Only higher resolution observations can determine if there are large velocity gradients within any given beam. However any such gradients are likely to be turbulent in nature since the broad ($b \geq 20\,\mathrm{km\,s^{-1}}$) line region is eight beam diameters wide.

Figure 14 compares the SPLOT b measurements with the azimuthally averaged b from the MOMNT and XGAUS results. It shows that the SPLOT and XGAUS results are in good agreement, indicating that the additional beam smearing in the $30''$ pixel data has not substantially increased b with respect to the full resolution UN data. The MOMNT analysis, on the other hand, yields b substantially lower than the Gaussian fits. This is due to an artificial bias in the MOMNT analysis technique; MOMNT only uses the data where the signal is above a certain threshold in a smoothed version of the data cube. This systematically excludes the profile wings, and thus the results are biased towards lower b.

The dotted line in Fig. 14 shows the two pixel resolution of the UN data cube ($b = 2.8\ \mathrm{km\,s^{-1}}$). Most profiles are well sampled by our data, those having $b \lesssim 2.8\ \mathrm{km\,s^{-1}}$ mostly have low signal to noise ratios. A notable exception is shown

[2] Since the line widths along the minor axis are not elevated relative to the major axis, it is not likely that residuals are due to a galactic wind.

in Fig. 13f. At large R, the mean b is around $8\ \mathrm{km\,s^{-1}}$, which is typical for disk galaxies (Kamphuis, 1992). Figure 13 shows that at this width the profiles remain well sampled.

4.3. Asymmetric drift correction

The broadening of the H I profiles in the central region is significant compared to the measured rotation, as can be seen by comparing Fig. 14 with Fig. 9. The random motions of the gas may then provide significant dynamical support in the central region. It is not clear that the gas there is in dynamical equilibrium. Indeed the asymmetry of the b map suggests that it is not. Nevertheless, here we will assume that gas is in equilibrium and account for the pressure support by estimating an "asymmetric drift" correction following Oort (1965; see his eq. 10). We assume that the gas velocity ellipsoid (*i.e.* pressure) is isotropic. This greatly simplifies the correction[3]. In a cylindrical coordinate system, the radial (R) acceleration K_R about the rotation axis z is given by

$$-K_R = \frac{{V_{\mathrm{rot}}}^2}{R} - b^2\frac{\partial(\ln[\rho b^2])}{\partial R},$$

where ρ is the density. If there were no pressure support the orbits would be circular with velocities V_c given by

$$\frac{V_c^2}{R} = -K_R.$$

The density can be written as $\rho = \Sigma_g/(2h_z)$, where h_z is the vertical scale height and Σ_g the gas surface density (here taken as H I plus neutral He). The circular velocity is then

$$V_c^2 = {V_{\mathrm{rot}}}^2 + \sigma_D^2 \tag{1}$$

[3]Binney and Tremaine (1978) treat the case of the asymmetric drift in collisionless systems (stars only) which have non-isotropic velocity ellipsoids.

where σ_D is the asymmetric drift correction given by

$$\sigma_D^2 = -Rb^2\left[\frac{\partial\ln(\Sigma_g)}{\partial R} + 2\frac{\partial\ln(b)}{\partial R} - \frac{\partial\ln(h_z)}{\partial R}\right]. \tag{2}$$

Usually the contributions of each of the gradients are zero or negative, making the correction positive. We do not have a direct measurement of h_z but will assume $\partial\ln(h_z)/\partial R = 0$. The other two terms can be estimated from the radial profiles of $\ln(b)$ and $\ln(\Sigma_g)$ which are shown in Fig. 15. Both profiles have a core-halo structure and are well fit by a function consisting of a Gaussian centered at $R = 0$ on top of a polynomial (in R) background:

$$\begin{aligned}
\ln(b) &= 2.40 + 6.57\times10^{-4}R \\
&\quad +1.23\exp(-\{R/85.1\}^2/2) \qquad (3)\\
\ln(\Sigma_g) &= 0.812 + 1.057\times10^{-3}R \\
&\quad -7.13\times10^{-6}R^2 \\
&\quad +1.51\exp(-\{R/56.2\}^2/2) \qquad (4)
\end{aligned}$$

where R is in arcsec, b is in $\mathrm{km\,s^{-1}}$, and Σ_g is the gas surface density in $\mathcal{M}_\odot\,\mathrm{pc}^{-2}$. The fits were unweighted and have an rms of 0.05 and 0.07 in $\ln(b)$ and $\ln(\Sigma_g)$ respectively. These fits (converted to linear units) are shown in Fig. 15, as well as the σ_D curve resulting from differentiating the fits. The last two columns of Table 3 tabulate σ_D and the corrected circular velocities, V_c. As expected the σ_D corrections are quite significant for $R \leq 152''$. We can now proceed to model the mass distribution, with the caveat that the H I may not be equilibrium at these radii.

4.4. Mass models

Three component mass models were fit to the rotation curve. The components are the stellar disk, a neutral ISM (H I) disk, and a dark matter (DM) halo. The stellar mass distribution is determined from the surface brightness profiles in paper I, and has one free parameter $\mathcal{M}/L_B$. The mass distribution of the H I disk (ncluding

neutral He) is determined from the observations presented here, and there are no free parameters. The DM halo is assumed to have a spherically symmetric density distribution given by

$$\rho = \frac{\rho_0}{1 + (R/R_c)^\gamma} \tag{5}$$

where the free parameters are the central density ρ_0 and the core radius R_c. Here we adopt $\gamma = 2$. For this density distribution the rotational velocity at large R, V_∞, and halo velocity dispersion σ_0 are given by (Lake *et al.* 1990):

$$V_\infty^2 = 4\pi G \rho_0 R_c^2 = 4.9\sigma_0.$$

Fitting was done with a χ^2 minimization technique. Thus the fitted parameters depend not only on the input data, but also the associated errors.

We experimented with numerous schemes for assigning errors to the V_c values in Table 3. These included adopting the $V_{\rm rot}$ errors, combining the $V_{\rm rot}$ errors with likely σ_D errors, and taking local averages of the errors over several rings. In the end we adopt a uniform error in V_c of 3 $\rm km\,s^{-1}$. This corresponds to the average error in $V_{\rm rot}$ for $R > 90''$. The other methods invariably assign less weight to the inner points than to the outer points. The χ^2 minimization then effectively sacrifices the fit in the inner regions in order to make a marginal improvement at large R. Only equal weighting produces a reasonable fit at all R. So for the adopted fits we are no longer doing true χ^2 minimization, but effectively a non-weighted least squares minimization. Four models are discussed. They are illustrated in Fig. 16, and their parameters are tabulated in Table 4. Each panel of Fig. 16 shows the fitted rotation curve and the contribution of each of the components.

Model A is the best fit to the V_c data. All three parameters are allowed to be free, with the only constraint that they be ≥ 0. The resulting fit has $\mathcal{M}/L_B = 0.0$, i.e. the disk is not needed to fit the rotation curve. The halo parameters are for a very compact and dense core, the most extreme of the models generated here.

Model B is a fit to $V_{\rm rot}$ instead of V_c; in effect it ignores the pressure support. The difference between Models A and B is thus indicative of the uncertain dynamical state of the central region. Neglecting the asymmetric drift correction results in a larger, less dense core. The effect on the inferred core parameters is quite dramatic, a factor of about 1.5 in R_c and more than 2 in ρ_0. Since we may have underestimated σ_D, it is possible that NGC 2915's halo is even more dense and compact than that of Model A. Like model A, model B yields $\mathcal{M}/L_B = 0.0$.

Model C shows a fit where the DM halo is a non-singular isothermal sphere (e.g. Binney & Tremaine 1987). For this density distribution

$$\sigma_0 = \frac{2}{3} R_c \sqrt{\pi G \rho_0} = \frac{V_\infty}{\sqrt{2}}.$$

This is the form of the DM distribution usually favored by Carignan and collaborators (e.g. Puche & Carignan, 1991, and references therein). It is clear that model A is a better fit over all radii, but model C produces as good or better of a fit for $R \leq 6$ kpc. The difference between Models A and C illustrates the uncertainty due to which arbitrary form of the halo distribution is adopted. The isothermal sphere and the analytic form of eq. 5 have significantly different scaled density profiles over their first few R_c. Thus model C has very different parameter values than A and B. It has a much less dense core, and it is the only one of the three with a non-zero $\mathcal{M}/L_B$ as the best fit.

Models A-C give the best fit value with all parameters free. The resulting limits on $\mathcal{M}/L_B$ are lower than one would expect for the red color of the outlying diffuse stellar population in NGC 2915. For Model D we return to the analytic halo models given by eq. 5 and fix $\mathcal{M}/L_B = 1.2$, which represents approximately the maximum the disk component can contribute to match the innermost V_c data point. This mass

to light ratio is in the range expected for the colors of NGC 2915 ($1 \lesssim M/L_B \lesssim 3$; Bruzual and Charlot, 1993). The resultant halo parameters turn out to be identical to model B. In this case the disk contribution to $V_c(R)$ is of the same order as the σ_D corrections. Likewise models of type C, but with no σ_D corrections, produce negligible disk contributions. Thus the strength of the disk component critically depends on the σ_D corrections. Fits using the R band light profile (paper I) are not significantly better in fitting the rotation curve than the B profile used here. Model D is our preferred fit, since the limits on $\mathcal{M}/L_B$ are implausibly low for models A and B, and model D is clearly a better fit than model C.

Note that models A, B and D have very similar values V_∞ with low uncertainties. This is because V_∞ essentially determines the level of the flat part of the rotation curve, which is constrained much better than the inner portions. V_∞ is lower for model C because the isothermal sphere reaches a maximum V_c of $1.1V_\infty$, and does not approach V_∞ until $R \gtrsim 10R_c$ (Binney & Tremaine 1987).

None of the models can produce the exact shape of the rotation curve, especially the upturn in $V_{\rm rot}$ at large R. We performed fits where γ in eq. 5 is a free parameter. These yield $\gamma = 1.93$ and are not a significant improvement over Model A. The ± 8 km s^{-1} modulations in the V_c profile occur where the b profile and residual maps show significant non-circular motions. One should not over-interpret them as necessarily reflecting structure in the mass distribution.

5. Discussion

5.1. Comparison with other galaxies

NGC 2915 is an intriguing galaxy because its optical properties are those of a weak BCD (paper I) while its H I morphology and global profiles are those of an Sd-Sm disk galaxy (cf. Roberts and Haynes, 1994; Shostak, 1978). It has both a bar and a strong warp. These are normal properties of spiral galaxies (Holmberg 1958; Bosma 1991). NGC 2915 appears to be a two armed system. The arm structure is not flocculent like the transient features seen in simulations of shearing disks (e.g. Gerola & Seiden, 1978), despite occurring in the flat (shearing) part of the rotation curve. The arms are therefore probably due to a spiral density wave. Although the kinematic signature of such a wave is not apparent, this may be due to the quality of the data (low signal to noise, insufficient resolution).

NGC 2915's H I extends well beyond $R_{\rm Ho}$ which is common for galaxies with high $\mathcal{M}_{\rm HI}/L_B$ ratio (Huchtmeier & Seiradakis, 1985; Hoffman *et al.*, 1993; van Zee *et al.* 1995). Its Σ_g profile has a core-halo structure. This is less common for spiral galaxies which typically exhibit an H I deficit or plateau in the center (Wevers *et al.* 1986; Warmels, 1988), although similar cores have been found in irregular galaxies (e.g. NGC 55; Puche *et al.*, 1991). NGC 2915's velocity dispersion profile also stands out for the high value, $b \approx 40$ km s^{-1}, in the center. This is much higher than seen in normal (non-bursting) disk galaxies, which typically reach a central maximum of $b \approx 15$ km s^{-1}, dropping to 6 to 8 km s^{-1} at large radii (e.g. Dickey *et al.*, 1990; see also comparisons of Kamphuis, 1992; Lo *et al.* 1993). Note that although NGC 2915 has a normal $b = 8$ km s^{-1} beyond the optical radius, it is unclear how it and other galaxies with extended H I disks maintain this velocity dispersion beyond any apparent heat sources.

The H I properties of NGC 2915 are less abnormal compared to the relatively few BCD and amorphous galaxies imaged in H I. These galaxies typically contain extended H I disks well beyond the optical radius, core-halo $\Sigma_{\rm HI}$ profiles and b profiles reaching 25 to 40 km s^{-1} in the center (Taylor *et al.* 1994; 1995; Hunter *et al.* 1994; Meurer 1994; Brinks 1988; Viallefond & Thuan, 1983). The properties of NGC 2915 are also reminiscent of the starburst IBm gal-

axy NGC 4449 which has an H I disk over ten times larger than its optical size (Bajaja *et al.*, 1994). This is not to say that NGC 2915 is a typical BCD. None of the BCDs that have been imaged at H I have spiral arms. Only 8% of BCDs have double horn profiles and the large gas to stars ratio $M_{\rm HI}/L_B = 2.7$ of NGC 2915 also stands out amongst BCDs, which have a median $M_{\rm HI}/L_B = 0.2$ (Thuan & Martin, 1981).

Less is known about the DM content of BCDs. This paper presents the first mass model decompositions of a BCD. When H I extends well beyond $R_{\rm Ho}$ and the rotation curve is flat, the result is a high $\mathcal{M}_T/L_B$ ratio. This is certainly true for NGC 2915 which has $\mathcal{M}_T/L_B = 76$ (model D) compared to DDO154 with $\mathcal{M}_T/L_B = 74$ (Carignan and Beaulieu, 1989; Hoffman *et al.* 1993) and DDO170 with $\mathcal{M}_T/L_B = 57$ (Begeman *et al.* 1991; Lake *et al.* 1990). Thus NGC 2915 is one of the darkest disk galaxies known. We note that the $\mathcal{M}_T/L_B$ values for giant ellipticals and dwarf spheroidals are similarly large (e.g. Grillmair *et al.*, 1994; Mateo *et al.* 1993).

It is not just the extent of NGC 2915's H I that distinguishes its remarkable DM properties. The DM core also appears to be extraordinarily dense with $\rho_0 \approx 0.1\,\mathcal{M}_\odot\,{\rm pc}^{-3}$ which is about an order of magnitude denser than typically found in disk galaxies (Skillman *et al.* 1987; Puche & Carignan, 1991; Begeman *et al.* 1991), but in the range of that found in dwarf spheroidal galaxies $\rho_0 = 0.07$ to $1.5\ \mathcal{M}_\odot\,{\rm pc}^{-3}$ (Mateo *et al.*, 1993).

Neither the core size, $R_c \approx 1$ to 3 kpc, nor $V_\infty = 73$ to $90\,{\rm km\,s^{-1}}$ (depending on model form) are particularly distinguishing; similar values of R_c are found in dwarf irregular galaxies, while low to moderate mass spirals have similar values of V_∞ (Puche & Carignan 1991; and references therein). But having both a high V_∞ and short R_c is rare. One exception is NGC 5585. Côté *et al.* (1991) fit a mass model, including an isothermal DM halo, to its rotation curve and find $R_c = 2.8$ kpc, $V_\infty = 76\ {\rm km\,s^{-1}}$, and $\rho_0 = 0.060\,\mathcal{M}_\odot\,{\rm pc}^{-3}$, i.e. nearly identical to our model C. But, whereas NGC 2915 is a BCD, NGC 5585 is a Sd IV spiral with $R_{\rm Ho} = 6.5$ kpc, over twice as large at optical wavelengths as NGC 2915. This striking difference suggests that the optical morphology of galaxies is independent of the properties of their DM halo. NGC 5907, with $\rho_0 \approx 0.08 - 1.9\,\mathcal{M}_\odot\,{\rm pc}^{-3}$ (Sackett *et al.*, 1994) also has one of the highest inferred ρ_0 for a disk galaxy. But in this case R_c is not well constrained by the rotation curve and ρ_0 refers to faint luminous matter, and not strictly speaking to, "dark" matter.

It should be noted that most of the studies quoted above adopt distances based on $H_0 = 75\,{\rm km\,s^{-1}\,Mpc^{-1}}$. Although the distance to NGC 2915 does not explicitly depend on H_0, it is tied to the distance to NGC 5253 derived by Sandage *et al.* (1994) who find $H_0 = 54\,{\rm km\,s^{-1}\,Mpc^{-1}}$ (paper I). We reran our preferred model, D, taking $D = 3.1$ Mpc for NGC 2915, which is more appropriate for $H_0 = 75\,{\rm km\,s^{-1}\,Mpc^{-1}}$ (here D is derived from V_r using a Virgo-centric flow model, and the appropriate $D_{\rm Virgo}$), and fixing $\mathcal{M}/L_B = 2.0$. The results make NGC 2915 appear more extreme: $R_c = 0.71 \pm 0.08$ kpc, and $\rho_0 = 0.31 \pm 0.06\,\mathcal{M}_\odot\,{\rm pc}^{-3}$ ($\sigma = 30.5 \pm 0.7$ ${\rm km\,s^{-1}}$). If NGC 2915 were this close it would have $\mathcal{M}_T/L_B = 130$ at its last measured point. A comparison of optical and DM halo properties of galaxies employing a uniform H_0 would be highly desirable.

5.2. Central Energetics

The neutral ISM is very energetic in the central bar area of NGC 2915. The energy is displayed in two forms: that in expanding structures, and general turbulence. The former is characterized by split lines implying an expansion velocity of $V_{\rm exp} = 0.5\Delta V$, where ΔV is the amount of line splitting. The expansion energy is

$$E_k({\rm exp}) = \frac{1}{8}\mathcal{M}_g \Delta V^2;$$

we take the mass involved in the expansion to be $\mathcal{M}_g = 10^8\,\mathcal{M}_\odot$ (the neutral gas mass within the central bar area) and $\Delta V = 40$ km s^{-1}, and derive $E_k(\exp) = 4 \times 10^{53}$ ergs. This is an overestimate since not all of $\mathcal{M}_g$ is likely to be in expanding structures. For an isotropic velocity distribution the turbulent energy is given by

$$E_k(\mathrm{turb}) = \frac{3}{2}\mathcal{M}_g\langle b_{HI}\rangle^2,$$

where $\langle b_{HI}\rangle = 35$ km s^{-1} is the mean velocity dispersion in the core. Thus $E_k(\mathrm{turb}) = 3.8 \times 10^{54}$ erg. The energy in turbulence appears to be significantly greater than that in expansion, although beam smearing may cause some confusion between bulk flows and turbulence. We adopt a total kinetic energy of

$$E_k = E_k(\exp) + E_k(\mathrm{turb}) = 4.2 \times 10^{54}\,\mathrm{erg}.$$

What is the source for this kinetic energy? Figure 17 (plate XXXX) shows the b contours of Fig. 8 overlaid on the Hα image of Marlowe *et al.* (1995). This shows the "smoking gun" that implicates hot young stellar populations with the energized neutral ISM. There are two Hα bubbles, of a blister morphology. That is their ionizing clusters are at the edges of the bubbles (near the galactic center), and the bubbles are expanding away from these clusters. While, the profiles are broad over the whole ionized region, notice that The protrusion in the $b = 30$ km s^{-1} contour about $25''$ to the north of the optical center clearly corresponds to the Hα bubble extending along the optical minor axis. The most energetic H I is associated with the SE H I cloud. It is at the edge of the SE Hα bubble which appears to be expand into it. Thus the broad H I profiles are associated with the turbulent ionized ISM and in particular the expanding Hα bubbles. The ultimate energy source is the stellar winds and SNe produced by the young central stellar populations.

For a solar metallicity population with a Salpeter (1955) IMF and a constant star formation rate, the equilibrium ratio $L_{\mathrm{mech}}/L_{\mathrm{H}\alpha} = 1.8$ (Leitherer and Heckman, 1995), where L_{mech} is the rate mechanical energy is produced by supernovae explosions and stellar winds. From the $L_{\mathrm{H}\alpha} = 6.4 \times 10^{39}\,\mathrm{erg\,s^{-1}}$ (paper I; Marlowe *et al.* 1994) we deduce $L_{\mathrm{mech}} \approx 1.1 \times 10^{40}\,\mathrm{erg\,s^{-1}}$. The crossing time of the core is $t_{\mathrm{cross}} \approx 3.1\,\mathrm{kpc}/35\,\mathrm{km\,s^{-1}} = 87$ Myr (i.e. the length of the region divided by the typical velocity). During this time the mechanical energy release of the central population is $E_{\mathrm{mech}} = L_{\mathrm{mech}}t_{\mathrm{cross}} = 3 \times 10^{55}$ erg, or seven times E_k. Only 10% – 20% of L_{mech} is likely to end up as kinetic energy, the rest being thermalized (Ostriker & McKee, 1988; Mac Low & McCray, 1988). So to a first approximation, the energy released by the young central population in NGC 2915 is sufficient to explain the observed kinetic energy in the neutral ISM.

5.3. Tully-Fisher Relationship

Figure 18 shows NGC 2915 and DDO154 in the absolute magnitude versus H I line width diagram. The tight correlation shown by the filled circles (Sandage and Tamman, 1976) and $\times$'s (Sandage, 1988), is the Tully-Fisher (1977) relationship (TFR) for nearby galaxies. NGC 2915, like DDO154 (Carignan and Beaulieu, 1989), falls way off this correlation. This discrepancy is also apparent in other recent calibrations of the TFR (e.g. Pierce and Tully, 1988) when the data is adjusted to the same value of H_0. Carignan and Beaulieu (1989) note that DDO154 shows the TFR may break down at the low mass end. NGC 2915 shows that it does not always hold even for moderate masses.

Milgrom and Braun (1988) note that the TFR should probably be considered a correlation between luminous matter - defined as stars and all phases of the ISM - and line width, not just optical luminosity and line width. The TFR holds for most galaxies because the stellar mass dominates over the ISM. However, for NGC 2915 and DDO154 the neutral gas component is more

significant than the stellar component. If their ISM were converted to stars with a $\mathcal{M}/L_B = 0.3 - 0.4\,(M/L_B)_\odot$ (higher if there is a significant mass in molecular gas) they would fall on the TFR. Thus under this scenario, the discrepancy with the TFR may indicate that the disks of DDO154 and NGC 2915 are relatively unevolved compared to normal galaxies.

There still remains the problem of the distribution of luminous matter and the TFR. In a normal TFR galaxy, the stellar distribution, which dominates the luminous mass, is much more concentrated than the DM. The contributions of each component to the rotation curve produces similar maximum values $V_{\rm max}$, but at different radii, such that the overall rotation curve is nearly flat at $V_{\rm rot} = V_{\rm max}$ from about a disk scale length out to the last measured point. This is the so-called "disk-halo conspiracy". If the neutral ISM of the discrepant galaxies were transformed to stars *in situ* such that the resultant luminosity is on the TFR, the stellar distribution will be coextensive with the DM (see below) and have $V_{\rm max}$ well below that of the DM. In other words there would be no disk-halo conspiracy in such cases. Thus NGC 2915 and DDO154 would not look like normal TFR galaxies even if their ISM were converted into stars, unless their ISM were to become centrally concentrated before star formation. Likewise, one could adjust the distance or dust extinction A_B (see paper I) such that NGC 2915 falls on the TFR, but there would still be no disk-halo conspiracy and the stellar $\mathcal{M}/L_B$ would be negligible. So even then NGC 2915 would be unlike any normal TFR galaxy.

The coincidence of the central $b = 40\,{\rm km\,s^{-1}} = \sigma_0$ of the DM halo is perhaps a new twist on the disk-halo conspiracy (although one case does not make a conspiracy). We speculate on the meaning of this coincidence in §6..

5.4. Star Formation Threshold

Figure 19a shows the surface density of the contributors to the mass of NGC 2915 from model D: the neutral gas, Σ_g, the stars, Σ_*, and DM halo, $\Sigma_{\rm DM}$. Figure 19b shows the ratio of the first two of these with $\Sigma_{\rm DM}$. It is immediately apparent that the stars do not trace the DM very well, but the neutral gas does. A relatively flat $\Sigma_g/\Sigma_{\rm DM}$ profile is commonly observed in disk galaxies, as first pointed out by Bosma (1981; more recent examples include Carignan & Beaulieu, 1989; Carignan *et al.* 1990). Rotation curves of some galaxies are well fit by scaling the Σ_g profile by a constant factor to obtain the DM contribution (Carignan & Beaulieu 1989; Broeils, 1992).

Figure 19 also shows the critical density for high mass star formation, $\Sigma_{\rm crit}$ (Kennicutt, 1989) and $\Sigma_{\rm crit}/\Sigma_{\rm DM}$. Σ_g is less than $\Sigma_{\rm crit}$ by a factor of about 3 (range of 2 to 9), even in the center of NGC 2915 where high mass star formation is seen. When only the neutral ISM is considered, NGC 2915 does not obey Kennicutt's star formation law. The discrepancy between Σ_g and $\Sigma_{\rm crit}$ is worst in the center of NGC 2915 because $\Sigma_{\rm crit} \propto b$, and this is where b is the highest. However, even adopting a constant $b = 5\,{\rm km\,s^{-1}}$ profile does not bring $\Sigma_{\rm crit} < \Sigma_g$. This is contrary to what is found for a wide variety of galaxies including both low surface brightness galaxies (van der Hulst *et al.* 1993) and other BCDs (Taylor *et al.*, 1994) which obey the Kennicutt law when *only* the neutral ISM is considered. Of course there may be no real discrepancy, since much of the ISM may be in molecular form. Star formation in NGC 2915 occurs at $R \leq 30''$ (paper I), where $\Sigma_{\rm crit}/\Sigma_g \approx 9$ and $M_g(R \leq 30'') = 3.1 \times 10^7$ $\mathcal{M}_\odot$. Thus to satisfy Kennicutt's law there should be $M_{\rm molecular} \geq 3 \times 10^8\ \mathcal{M}_\odot$. Only about 1% of the so-called dark matter need be molecular gas for the Kennicutt law to hold.

The peak H I surface density occurs in the two central H I clouds and is $\Sigma_{\rm HI} = 2.4 \times 10^{21}\,{\rm cm^{-2}}$

or after inclination correction $\Sigma_{\rm HI} = 1.2 \times 10^{21}$ cm^{-2}. Recent high mass star formation is seen near the positions of both these clouds. Star formation in NGC 2915 is consistent with "simple" H I threshold schemes for high mass star formation; for example Gallagher and Hunter (1984) propose that efficient high mass star formation occurs where $\Sigma_{\rm HI} > \Sigma_{\rm HI,crit} = 5 \times 10^{20}\,{\rm cm}^{-2}$, while Skillman (1987) similarly proposes that $\Sigma_{\rm HI,crit} = 10^{21}\,{\rm cm}^{-2}$. Thus although, the more complex star formation law of Kennicutt (1989) does not hold for NGC 2915, a simple threshold law does.

Kenney *et al.* (1993) show how tidal shear can limit star formation via cloud destruction. In NGC 2915 and the BCDs in the sample of Taylor *et al.* (1994), the star forming region and indeed most of the optically visible galaxy is located in the rising portion of the rotation curve. This is where the rotation is almost solid body, and thus tidal shear is minimized. Similarly the galaxies in the Skillman (1987) study all have solid body rotation where their H II regions are located.

6. Conclusions / Summary

Our detailed H I study of the weak BCD galaxy NGC 2915 shows it to have a nature unexpected from its optical appearance. The H I morphology and global properties (mass, line width) are those of a late type barred spiral galaxy. The presence of a bar is confirmed by the signature of an oval distortion in the velocity field. At our highest resolution the bar is resolved into two H I clouds separated by 1.5 kpc. The H I line of sight velocity dispersion in this central region is very high, $b \approx 40$ km s^{-1}, and the H I line is split by $\Delta V \approx 40$ km s^{-1} at the position of both H I clouds. The energetics of the central region can be accounted for by the known young stellar populations there. The H I extends well beyond the optical galaxy, out to five times the Holmberg radius. At these radii, the dynamics are dominated by rotation, although there are indications of an oval distortion in the velocity field, and some warping of the disk. The rotation curve is approximately flat for $R > 4$ kpc, but slightly rising at the last measured points ($R \gtrsim 10$ kpc). For $R < 3$ kpc, random motions are significant and there are indications that the systemic velocity varies with radius. It is not clear whether the system is in equilibrium at these radii.

The rotation curve can not be accounted for by the luminous components alone. Large amounts of dark matter (DM) are required, dominating at nearly all radii. Within the radius of the last measured point ($R = 15.2$ kpc) the total mass to blue light ratio is $\mathcal{M}_T/L_B = 76$, making NGC 2915 one of the darkest disk galaxies known. The complex dynamics of the central region, make interpretation of mass model fits to the rotation curve difficult. Despite this uncertainty, it is clear that NGC 2915's DM distribution has an unusually dense (central density $\rho_0 \approx 0.1\,\mathcal{M}_\odot\,{\rm pc}^{-3}$) and compact core (radius $R_c = 0.8$ to 2.5 kpc). The disk $\mathcal{M}/L$ ratio is not well constrained by our models, although it seems likely that the stellar component is less massive than the neutral ISM disk.

NGC 2915 does not obey the Tully-Fisher (1977) relationship, being under luminous by a factor of ten for its line width (or rotational velocity). Nor does it obey the Kennicutt (1989) star formation threshold law. Unless there is considerable amount of molecular material, its gas density is always below the critical density for high mass star formation, even in the center where high mass stars are observed to have formed recently. However, it does obey simple critical density threshold models for high mass star formation (c.f. Gallagher & Hunter 1984; Skillman 1987).

Finally we speculate on the nature of star formation in NGC 2915, a topic our observations shed new light on. In particular they reveal two key ingredients in its recipe for regulating star formation: a bar, and a deep central potential.

Friedli & Benz (1995) showed through numerical simulations that there is a complex interaction between star formation, the ISM, and the bar in isolated barred galaxies. The bar redistributes angular momentum resulting in an inflow along the bar. Some star formation along the bar energizes the ISM (via the resultant supernovae explosions and stellar winds) enough to inhibit additional star formation until the material reaches the center. The coincidence in velocity dispersions, that of H I measured in the center of the galaxy, and that inferred for the DM halo, suggests that the intensity of the central star formation is regulated by the depth of the potential well (Bothun *et al.*, 1986); if the star formation becomes too strong the ISM is thrown clear of the core and star formation is halted, at least temporarily. Some models indicate that such an outflow can contribute to the spin down of the disk resulting in further inflow (Corbelli & Salpeter, 1988; Charlton & Salpeter, 1989) thus establishing a "galactic fountain". The stellar component of NGC 2915 and other BCD/amorphous galaxies is limited to within the turnover radius indicating that tidal shear probably strongly inhibits star formation. The optical images of NGC 2915 has the size and orientation of the central bar, suggesting that the stellar counterpart is a bar, or at least that the bar axis is coincidentaly the optical major axis. A scenario of bar and DM regulated star formation for NGC 2915 does not require interaction, which is convenient since NGC 2915 is in a low density environment. However, there is one possible interaction partner (Appendix) so an interaction model such as that sketched by Noguchi (1988) or Taylor *et al.* (1993) can not be ruled out.

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A. Appendix: an interaction partner?

Taylor *et al.* (1993; 1995; 1996) surveyed apparently isolated BCDs for companions with the rationale that interaction with an unseen companion may be responsible for the BCDs present burst of star formation. Such companions were successfully found in 12/21 galaxies in their sample. We unsuccessfully searched our H I data cube for faint companions. However the primary beam of the AT dishes is $W_{50} = 33'$ which corresponds to a radius of 25 kpc. At a typical relative velocity of 300 km s^{-1} an interacting partner can transverse this distance in less than 100 Myr.

We searched the NASA/IPAC Extragalactic Database (NED)[4] for possible interaction part-

[4]The NASA/IPAC Extragalactic Database (NED) is op-

ners within 5° of NGC 2915. There are no galaxies with cataloged velocities within 500 $\mathrm{km\,s^{-1}}$ of NGC 2915's. However there is one low surface brightness object, SGC0938.1-7623, which is separated from NGC 2915 by $42'$, a projected distance of 64 kpc, and has no measured velocity. Is SGC0938.1-7623 the interacting partner of NGC 2915?

Unfortunately the answer is not yet clear. Corwin *et al.*, (1985) note that it is not certain whether SGC0938.1-7623 is a low surface brightness galaxy or diffuse nebulosity associated with our galaxy. Figure 20 shows an I band CCD image of SGC0938.1-7623 obtained using the F1 imaging system on the AAT. It was made from four 200s exposures obtained during non-photometric conditions. There are numerous foreground stars over the face of SGC0938.1-7623, but no obvious overabundance of sources that would suggest SGC0938.1-7623 is resolved. The main body has a diameter of $\sim 130''$. There are faint extensions to the SE and NW yielding a total diameter of $\sim 270''$. The overall symmetry of the system suggests that it is a galaxy.

An H I spectrum in the direction of SGC-0938.1-7623 was obtained with the Parkes 64m radio telescope. The observations cover the range $V_r = -1000$ to $+4000$ $\mathrm{km\,s^{-1}}$ split over 1024 channels and reach a noise level of 50 mJy. There are no obvious H I features in the spectrum except for strong galactic H I and a narrow spike having $V_r = 300$ $\mathrm{km\,s^{-1}}$, $W_{50} = 30$ $\mathrm{km\,s^{-1}}$, and $\int S dv = 0.72 \pm 0.06$ Jy $\mathrm{km\,s^{-1}}$. This probably corresponds to the edge of the high velocity cloud HVC 300–24+274, which Morras (1982) shows to have narrow profiles and velocities varying over the range $240 \lesssim V_r \lesssim 330$ $\mathrm{km\,s^{-1}}$.

We conclude that there is no evidence that SGC0938.1-7623 is interacting with NGC 2915. However, it can not yet be ruled out as an interaction partner. For an assumed 50 $\mathrm{km\,s^{-1}}$ line width the H I spectrum should be able to detect $\mathcal{M}_{\rm HI} > 2.6 \times 10^6\ \mathcal{M}_\odot$ with $S/N > 5$ at NGC 2915's distance. If SGC0938.1-7623 is at the distance of NGC 2915 it is gas poor.

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Fig. 1. Contour plots of the channels with signal in the CLEANed NA data cube. The contour levels are at 10, 25, 50, 75, and 90 percent of the peak surface brightness of 4.7 Jy beam^{-1} ($N_{\rm HI} = 1.69 \times 10^{20}\,{\rm cm}^{-2}$). The V_r in ${\rm km\,s^{-1}}$ of each channel is shown in the upper right of each panel. The beam size ($W_{50} = 45''$) is shown on the lower left of the upper left panel, and again four panels beneath it.

Fig. 2. Grey scale representations of H I intensity maps, all to the same scale. Top panel is the NA moment 0 map ($45''$ resolution). The middle panel is the UN moment 0 map ($25''$ resolution). The bottom panel shows the peak intensity (amplitude) from the XGAUS single Gaussian fits to the UN data. North is up and east is to the left in all panels. The scalebar in the bottom panel is $2'$ long and $20''$ wide.

Fig. 3. Contour plot of total H I intensity from the NA zeroth moment map. Contour levels are at 2.5, 7.5, 15, 25, 50 75, and 90 percent of the peak H I surface brightness of 3.1 Jy beam^{-1} ${\rm km\,s^{-1}}$ ($N_{\rm HI} = 1.71 \times 10^{21}\,{\rm cm}^{-2}$). In this and the remaining maps the crosses mark the positions of fiducial stars and the star marks the optical center from paper I, and the beam size is shown in the lower left corner.

Fig. 4. 800s I band CCD image of NGC 2915, obtained with the AAT F1 system overlain with H I total intensity contours from the UN moment 0 map. Contours are at 5, 13, 25, 50, 75, and 90 percent of the peak surface brightness of 1.39 Jy beam^{-1} ${\rm km\,s^{-1}}$ ($N_{\rm HI} = 2.46 \times 10^{21}\,{\rm cm}^{-2}$). The strong glow at lower right in this figure and Fig. 6 is due to a bright star just off the edge of the frame.

Fig. 5. Velocity field from the NA first moment map. The V_r in ${\rm km\,s^{-1}}$ of the contours are indicated.

Fig. 6. Velocity field from the UN first moment map overlain on the I band image. The contour interval is 10 ${\rm km\,s^{-1}}$. The contour passing through the center has $V_r = 470$ ${\rm km\,s^{-1}}$; the prominent closed contours to the SE and NW of the center have $V_r = 400$ and 540 ${\rm km\,s^{-1}}$, respectively.

Fig. 7 Global H I V_r profiles derived from the NA (solid line) and UN (dotted line) data cubes. The systemic velocity (first moment of the profiles) are indicated with arrows of the corresponding line type.

Fig. 8 Line broadening, b, map from automatic single Gaussian fitting using XGAUS. The results are shown as both a grey scale and contours at $b = 10, 20, 30, 40$ and 50 ${\rm km\,s^{-1}}$. Blank areas are regions of either low signal to noise or complex profiles which could not be fit with a single Gaussian.

Fig. 9 Results of the tilted ring analysis of the three velocity fields: NA-MOMNT, UN-MOMNT, and UN-XGAUS. The parameters shown are major axis position angle, ϕ; inclination i, and rotation velocity $V_{\rm rot}$.

Fig. 10 Contours through a position - velocity cut of the NA data cube. The cut is through the center of NGC2915 and at a position angle of $70°$, corresponding to the kinematic major axis. The X axis indicates location along this position angle; the tick marks are separated by $208''$. The contours are at -3.5, 3.5, 7, 14, 21, 28, and 35 mJy/Beam. Note the "second rise" in $V_{\rm rot}$ seen on both sides of the galaxy.

Fig. 11 Grey scale plus contour plots of the residual maps from the tilted ring fits. The contours shown are for $\Delta V_r = -20, -15, -10, -5, 5, 10, 15$ and 20 ${\rm km\,s^{-1}}$. Panels a, b, and c show the NA-MOMNT, UN-MOMNT, and UN-XGAUS residuals respectively. Note that the panels have different scales.

Fig. 12 Position with respect to the center of NGC 2915 (shown as a star) of SPLOT profile measurements. Positions marked with small dots are well represented by single Gaussian fits, while double Gaussians are required for the positions marked with large dots. The crosses mark the

position of the fiducial stars shown in Figs. 4,6.

Fig. 13 Examples of SPLOT Gaussian fits (continuous lines) to H I line profiles (histogram style lines). The profiles were chosen to illustrate (a) a typical high signal/noise outer profile; (b) a typical low signal/noise outer profile; (c) a broad single profile near the center; (d) a split profile near the center; (e) a split profile in the outer disk; (f) an atypical profile: a narrow core on top of a normal single profile. The positions of the profiles in $\pm$E, $\pm$N offsets (in arcsec) from the center of NGC 2915 are: (a) –295,101; (b) –25,311; (c) 5,11; (d) 35,–19; (e) –265,–79; (f) –325,41.

Fig. 14 Comparison of line of sight velocity dispersion, b, measurements. Azimuthal averages of the UN-MOMNT, and UN-XGAUS measurements are shown as filled squares and triangles respectively. Individual SPLOT measurements with signal/noise > 3 are shown as $\times$'s, lower signal/noise splot measurements are indicated with dots.

Fig. 15 The top panel shows the line of sight line broadening, b, as a function of radius, while the middle panel shows the gas surface density, Σ_g. The filled circles show the data which are azimuthal averages extracted from the UN-XGAUS b map (top) and UN zeroth moment maps (center) using concentric rings with $\phi = -60.8$, $i = 59.6$. The broken lines show the fits to these data as given in the text. The contribution of the b and Σ gradients to the total asymmetric drift correction, σ_D are shown in the bottom panel with the corresponding line style. The total Σ_D curve is shown as the solid line.

Fig. 16 The rotation curve with mass model fits. Triangles represent results from the UN-XGAUS data, circles from the UN-MOMNT data, and squares from the NA-MOMNT data. Closed symbols are V_c and open symbols $V_{\rm rot}$. The Holmberg radius is indicated by the arrow. The thick solid line in each panel shows the model fit, and the broken lines show the contribution of the individual components: stellar disk, dotted line; neutral gas, long dashed line; DM halo, short dashed line. See the text for a description of the individual models.

Fig. 17 Contours of line of sight velocity dispersion b overlain on the Hα image of Marlowe *et al.* (1994). The b contours correspond to those shown in fig. 8. The scale bar at lower right is $30''$ long.

Fig. 18 The Tully-Fisher relationship for nearby disk galaxies compared with DDO154 and NGC 2915. ΔV^i_{21} is the inclination corrected H I line width at 20% of the peak value, and M_B is the absolute B band magnitude. The solid circles are data from Sandage & Tamman (1976); the $\times$'s are from Table 2 of Sandage (1988). Galaxies with $i < 40°$ have been excluded from both samples and we have taken $M_B = M_{\rm pg} + 0.1$ where necessary.

Fig. 19 *Upper panel*: radial variation of logarithmic surface densities. The neutral gas measurements (solid line) are azimuthal averages using the UN data for $R \leq 10$ kpc ($390''$) and the NA data for $R > 10$ kpc. The projected DM density (dashed line) is that derived from model D. The stellar profile (dotted line) is the B band surface brightness profile (paper I) normalized to the $\mathcal{M}/L_B$ ratio of model D. The critical density required for efficient star formation (Kennicutt, 1989; dot dashed line) is derived from the rotation curve and the b fit of eq. 4. *Lower panel*: logarithm of surface densities normalized by $\Sigma_{\rm DM}$. Line styles are the same as for the upper panel.

Fig. 20 800 s I band CCD image of SGC0938.1-7623, obtained with the AAT F1 system. North is up East is to the left and the image is $500''$ across in each dimension.

Table 1

HI Observing Log

config. name	UT date	baseline range[a]	on source (hrs)
0.375	3 May, 1992	31 – 459	11.34
0.75 C	22 Jan, 1993	46 – 750	10.52
1.5 D	12 Mar, 1993	107 – 1439	10.80

[a]In meters, excluding baselines with antenna 6.

Table 2

Dataset properties

Quantity	NA value	UN value	units
beam W_{50}	45×45	27×23	arcsec $\times$ arcsec
pixel size	$14 \times 14 \times 6.62$	$10 \times 10 \times 3.31$	arcsec $\times$ arcsec $\times$ $\mathrm{km\,s^{-1}}$
noise/channel	2.9	3.0	10^{-3} Jy Beam^{-1}
$\int SdV$	145	139	Jy $\mathrm{km\,s^{-1}}$
$\mathcal{M}_{\mathrm{HI}}$	9.58	9.21	$10^8\,\mathcal{M}_\odot$
W_{50}(global)	151	146	$\mathrm{km\,s^{-1}}$
W_{20}(global)	170	163	$\mathrm{km\,s^{-1}}$
V_{sys}(global)	471	468	$\mathrm{km\,s^{-1}}$
V_{sys}(dynamical)	467	469	$\mathrm{km\,s^{-1}}$
R_{HI}	14.9	$\cdots$	kpc
N_{HI}(max)	0.88	1.26	$10^{21}\,\mathrm{cm^{-2}}$
$\mathcal{M}_{\mathrm{HI}}/L_B$	2.7	2.6	$(M/L_B)_\odot$
$R_{\mathrm{HI}}/R_{\mathrm{Ho}}$	5.2	$\cdots$	
$R_{\mathrm{HI}}/\alpha_B^{-1}$	22.6	$\cdots$	

Table 3

Results of tilted ring analysis.

R ($''$)	ϕ ($^\circ$)	i ($^\circ$)	$V_{\rm rot}$ ($\rm km\,s^{-1}$)	σ_D ($\rm km\,s^{-1}$)	V_c ($\rm km\,s^{-1}$)
27.5	-28 ± 12	73 ± 24	29 ± 17	26.5	39
52.5	-28 ± 11	78.0 ± 7.1	37 ± 22	38.1	53
77.5	-48.1 ± 2.1	63 ± 11	53 ± 27	37.7	65
102.5	-56.3 ± 0.8	74.8 ± 5.4	65.5 ± 2.0	31.5	72.7
127.5	-56.8 ± 3.9	73.1 ± 9.7	71.9 ± 9.0	24.6	76.0
152.5	-55.7 ± 4.2	70.3 ± 8.4	76.8 ± 6.7	19.0	79.2
177.5	-53.7 ± 0.6	62.2 ± 2.3	79.9 ± 1.3	15.2	81.4
202.5	-53.0 ± 0.6	56.0 ± 2.7	81.5 ± 1.0	12.6	82.5
227.5	-56.3 ± 0.5	53.8 ± 1.4	82.1 ± 4.6	11.2	82.8
252.5	-58.6 ± 1.7	55.2 ± 1.4	79.7 ± 4.6	10.5	80.4
277.5	-61.4 ± 1.9	53.0 ± 1.2	79.7 ± 3.7	10.5	80.4
302.5	-62.8 ± 2.1	52.2 ± 1.1	80.2 ± 1.6	10.8	80.9
327.5	-64.0 ± 1.0	53.1 ± 1.5	79.9 ± 0.7	11.3	80.7
352.5	-65.0 ± 1.1	53.8 ± 3.1	79.9 ± 1.5	11.9	80.8
377.5	-65.1 ± 1.0	54.6 ± 2.3	81.0 ± 0.7	12.5	82.0
412.5	-66.3 ± 0.4	56.2 ± 2.0	81.2 ± 3.2	13.3	82.3
457.5	-67.5 ± 1.6	58.4 ± 0.7	82.6 ± 2.1	14.3	83.8
502.5	-68.5 ± 2.2	58.7 ± 1.9	84.2 ± 1.5	15.2	85.5
547.5	-68.8 ± 0.9	58.9 ± 2.3	87.0 ± 0.5	16.1	88.5
592.5	-68.8 ± 0.5	58.2 ± 1.1	92.3 ± 1.3	16.9	93.9

Table 4
Mass models

Model:	A	B	C	D
Fit parameters :				
$\mathcal{M}/L_B$ (solar units)	< 0.4	< 0.14	0.75 ± 0.40	1.2
R_c (kpc)	$0.78^{+0.17}_{-0.07}$	$1.24^{+0.19}_{-0.09}$	2.5 ± 0.3	1.23 ± 0.15
ρ_0 ($\mathcal{M}_\odot \mathrm{pc}^{-3}$)	0.24 ± 0.06	0.10 ± 0.02	0.07 ± 0.02	0.10 ± 0.02
σ_0 ($\mathrm{km\,s^{-1}}$)	39.9 ± 0.8	41.2 ± 0.9	51.9 ± 0.9	41.0 ± 1.1
V_∞ ($\mathrm{km\,s^{-1}}$)	88 ± 2	91 ± 2	73 ± 1	91 ± 2
rms ($\mathrm{km\,s^{-1}}$)	2.8	3.8	4.1	3.8
Reduced χ^2	1.01	1.87	2.14	1.80
At R_{Ho} (2.9 kpc) :				
V_c ($\mathrm{km\,s^{-1}}$)	73	66	73	71
$\mathcal{M}_T$ ($10^9\,\mathcal{M}_\odot$)	3.6	3.0	3.6	3.4
$\mathcal{M}_T/L_B$ (solar units)	10.1	8.4	10.2	9.6
$\mathcal{M}_{\mathrm{dark}}/\mathcal{M}_{\mathrm{Luminous}}$	27	22	8.3	5.2
Within last point (15.2 kpc) :				
V_c ($\mathrm{km\,s^{-1}}$)	87	87	81	88
$\mathcal{M}_T$ ($10^9\,\mathcal{M}_\odot$)	27	27	23	27
$\mathcal{M}_T/L_B$ (solar units)	74	75	65	76
$\mathcal{M}_{\mathrm{dark}}/\mathcal{M}_{\mathrm{Luminous}}$	28	28	19	19

Note.—Errors are 90% confidence limits and upper limits are 95% confidence limits. They were determined from Monte-Carlo simulations assuming uniform V_c and V_{rot} errors of ± 3 $\mathrm{km\,s^{-1}}$.

Fig. 1.—

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Fig. 20.—